INSTITUTE OF GAS TECHNOLOGY

CHICAGO, ILLINOIS

STUDY OF THE FUNDAMENTALS OF COMBUSTION

REPORT NO. 8

BY

P.P. LEO
M.F. QUINN
E.F. SEARIGHT
R.E. PECK

CONTRACT NONR-04100

OCTOBER, 1953

OFFICE OF NAVAL RESEARCH

WASHINGTON, D.C.

INSTITUTE OF GAS TECHNOLOGY

TECHNOLOGY CENTER

CHICAGO 16, ILLINOIS

STUDY OF THE FUNDAMENTALS OF COMBUSTION

REPORT NO. 8

BY

P. P. LEO

M. F. QUINN

E. F. SEARIGHT

R. E. PECK

CONTRACT NONR-04100

FOR

OFFICE OF NAVAL RESEARCH

DEPARTMENT OF THE NAVY

WASHINGTON, D. C.

TABLE OF CONTENTS

LIST OF TABLES

Table

LIST OF ILLUSTRATIONS

ABSTRACT

This report presents the results of a study of the burning velocities of the methane-oxygen-argon and methane-oxygen-helium systems at a theoretical adiabatic flame temperature of 2000°K and one atmosphere pressure.

The data were obtained on a three-eighths inch diameter burner. The burning velocities of the mixtures were calculated by the total area method.

For the argon system a maximum value of burning velocity was found at an oxygen to methane ratio of 4.0:1.0. For oxygen to methane ratios of 1.6:1.0 to 6.0:1.0 lifting occurred at a Reynolds number of 1200 and it was necessary to decrease the flow rate to obtain stable flames.

For the helium system the burning velocity showed a maximum at an oxygen to methane ratio of 5.0:1.0. It was found necessary to decrease the flow rate of all methane-oxygen-helium mixtures to obtain stable flames. Reynolds numbers for these flow rates were between 80 and 650.

The compositions of thirteen mixtures were calculated for the methane-oxygen-inert gas system yielding a theoretical adiabatic flame temperature of 2000°K at one atmosphere pressure. The inert gas may be argon, helium or any other gas having the same molal heat capacity.

Several mixtures of the methane-oxygen-nitrogen, 2000°K system, previously unreported, were calculated and the burning velocities determined. These data were found to lie within experimental error of the previously determined curve.

INTRODUCTION

This report presents the results of the work performed during the period January 1, 1953 to June 30, 1953 on "A Study of the Fundamentals of Combustion," jointly sponsored by the Office of Naval Research, Science Division, Power Branch and by the Institute of Gas Technology in the laboratories of the Institute of Gas Technology at Chicago, Illinois.

The burning velocities of a series of twelve methane-oxygen-argon mixtures, and twelve methane-oxygen-helium mixtures were determined. These mixtures were calculated to yield a theoretical flame temperature of 2000°K at one atmosphere pressure. The methane to oxygen ratio was varied from 0.78:1.0 to 11.41:1.0. These data were obtained on a three-eighths inch diameter tube burner.

Also included are burning velocities of three methane-oxygen-nitrogen mixtures at a theoretical adiabatic flame temperature of 2000°K. The compositions of two methane-oxygen-nitrogen mixtures at 2000°K adiabatic temperature were calculated and are reported.

EXPERIMENTAL PROCEDURE

The gases* used in these determinations were metered separately through previously calibrated critical flow orifices, and were passed through a mixing "T" to a water jacketed three-eighths inch diameter burner tube. The burner tip was maintained at room temperature and was checked by a copper constantan thermocouple imbedded 0.1 inch from the tip.

All investigations were made at constant theoretical adiabatic flame temperatures of 2000°K and at a pressure of one atmosphere.

The Reynolds number was maintained at 1200 whenever possible. However, in some instances it was found necessary to reduce the flow rate to obtain a stable flame.

Photographs of the flames were taken and enlarged to approximately three times actual size. Since the inner cone height was the most reproducible measurement which could be made, it was used to calculate the burning velocity in the following equation:

$$V_B = \frac{V_G}{\sqrt{1 + 4\left(\frac{H}{D}\right)^2}} \qquad \text{Equation (1)}$$

where V_B = burning velocity (ft/sec)

V_G = velocity of unburnt gas (ft/sec)

H = inner cone height (ft)

D = burner diameter (ft)

*See Table I for analyses or gases used.

RESULTS

Methane-Oxygen-Argon System

The results of the burning velocity determinations on the methane-oxygen-argon system at 2000°K and one atmosphere pressure are listed in Table II and presented graphically in Figure 1. The burner inlet gas compositions are given in Table V. The equilibrium composition of the products are given in Table VI and Figures 7a and 7b.

For the mixtures with oxygen to methane ratios of 1.6:1.0 to 5.0:1.0 it was found that the flame would blow off when the Reynolds number of the gas was 1200. The burning velocity for the ratio of 6.0:1.0 was determined at a Reynolds number of 1200 and 1100. At 1200 the flame had a tendency to lift after burning for a short time. The values of burning velocity for these two flow rates agreed within 3%. The burning velocity for the oxygen to methane ratio of 5.0:1.0 was determined at Reynolds numbers 800 and 500. Agreement between the two values was within 1%.

The stoichiometric mixture had a very small range of stability, between Reynolds numbers of 90 and 135. A flat flame was photographed at a Reynolds number of 135. The burning velocity calculated at this Reynolds number was found to be low on the basis of the correlations shown in Figure 1. The same difficulty was encountered at the stoichiometric mixture for the methane-oxygen-nitrogen system.

A maximum burning velocity was found at the oxygen to methane ratio of 4.0:1.0 (Figure 1). Since at this ratio it was necessary to operate at a Reynolds number of 600 to achieve a stable flame, the presence of this maximum may be the result of radial diffusion or a tendency toward polyhedral flame formation. The lower flow rate, producing lower shearing stresses, favors such diffusional phenomena. This would shift the temperature from the calculated 2000°K isotherm, resulting in a different burning velocity. Future investigations should determine if this is the case.

It is observed (Figure 4) that in the methane rich region the methane-oxygen-argon and methane-oxygen-nitrogen systems are coincident.

The effect of nitric oxide on burning velocity was investigated by the addition of a small amount of nitric oxide to the combustible mixture at oxygen to methane ratios of 8.0:1.0 and 9.0:1.0. The burning velocity was unaffected. However, at the temperature encountered in the flame, the reaction

$$NO \longrightarrow 1/2\ N_2 + 1/2\ O_2$$

takes place. Due to this decomposition, the concentration of nitric oxide at the flame front is expected to be very low.

Methane-Oxygen-Helium System

The results of the burning velocity determination for the methane-oxygen-helium system are given in Table II and Figure 2. The composition of the burner inlet mixtures and the concentration of the equilibrium products of combustion are the same as those for the argon system since the molal heat capacities of the inert gases (argon and helium) are identical.

To obtain stable flames it was necessary to use very low flow rates. The resulting flames were small and there was some rounding at the tips. It is expected that some error will be introduced when the calculations are made on the basis of a right circular cone.

At the stoichiometric point the mixture could not be ignited at any flow rate. The concentration of methane in the mixture was close to the lower limit of combustibility in air and results show that the method concentration was below the combustible limit in the mixture.

Methane-Oxygen-Nitrogen System

The curve for the methane-oxygen-nitrogen data illustrated in Figure 3 is that given in Report No. 6, this project, with two additional points at the oxygen to methane ratios of 4.0:1.0 and 6.0:1.0. The point at 5.0:1.0 was used as a control. The results of the burning velocity determinations are given in Table IV. The burner inlet gas compositions and the equilibrium products of combustion are given in Tables VII and VIII, respectively. The data agree within 5-1/2% with that predicted by the curve on Figure 3.

Flame Temperature Calculations

It is possible to estimate the composition of a gas mixture that will give a theoretical adiabatic flame temperature if the stoichiometric point, the methane rich and oxygen rich point are calculated and plotted as in Figure 6. The intermediate points lie on approximately straight lines. Tables IX and X show a comparison of the calculated and estimated inert gas-methane ratios for the methane-oxygen-argon and methane-oxygen-nitrogen, 2000°K, systems, respectively.

CONCLUSIONS

1) Each of the methane-oxygen-inert gas systems with nitrogen, argon and helium as inerts at an adiabatic flame temperature of 2000°K and one atmosphere pressure exhibit maximum values. These maxima are at different oxygen to methane ratios for each system.
2) The addition of traces of nitric oxide to methane-oxygen-argon mixtures does not affect the burning velocity of the mixture.
3) The stoichiometric mixture of methane-oxygen-helium is below the combustible limit.

RECOMMENDATIONS

1) Determine the burning velocity of the methane-oxygen-argon system at the adiabatic flame temperature of 2250°K. This may indicate whether or not the maximum obtained at the methane to oxygen ratio of 4.0:1.0 (on the 2000°K isotherm) is due to a physical property of the specific mixture.
2) Determine the burning velocity of the nitrogen and helium systems at an adiabatic flame temperature of 2250°K and 2500°K to determine the effect of temperature on burning velocity.
3) Correlate burning velocity as a function of the transport properties of the system.

TABLE I

ANALYSES OF GASES BY MASS SPECTROMETER

Oxygen Mole %		Argon Mole %		Helium Mole %	
O_2	99.6	A	99.9	He	100.0
N_2	0.4	N_2	0.1		

Methane, Mole %

Cylinder 1 (Argon Data)		Cylinder 2 (Helium Data)	
CH_4	99.6	CH_4	98.8
C_2H_3	0.1	C_2H_6	0.6
C_3H_8	0.1	C_3H_8	0.3
N_2	0.1	N_2	0.1
CO_2	0.1	CO_2	0.2

TABLE II

EXPERIMENTAL DATA FOR THE METHANE-OXYGEN-ARGON SYSTEM AT 2000°K, ONE ATMOSPHERE PRESSURE

O_2/CH_4	(H/D) Cone Height / Port Diameter	Q Volumetric Flow, 25°C 29.92" Hg (ft^3/hr)	u, Velocity at 25°C 29.92" Hg (ft/sec)	N_{Re} Reynolds Number	Burning Velocity (ft/sec)
0.783	4.43	20.33	7.36	1200	0.825
0.783	4.37	20.33	7.36	1200	0.836
1.2	6.25	16.93	6.13	1200	0.489
1.2	5.91	16.93	6.13	1200	0.517
1.6	3.83	14.47	5.24	1050	0.678
1.6	3.76	14.47	5.24	1050	0.690
2.0	--	1.86	0.67	135	--
2.0	--	1.77	0.64	130	--
3.0	1.45	8.26	2.99	600	0.98
4.0	1.06	8.32	3.01	600	1.29
4.0	1.03	8.32	3.01	600	1.32
5.0	1.13	8.38	3.04	600	1.24
5.0	1.51	11.18	4.05	800	1.27
6.0	2.60	16.81	6.09	1200	1.15
6.0	2.48	15.50	5.61	1100	1.11
8.0*	2.63	17.25	6.25	1200	1.17
8.0	2.57	17.24	6.24	1200	1.20
9.0	2.50	17.25	6.25	1200	1.22
9.0*	2.53	17.36	6.29	1200	1.23
9.0	2.51	17.36	6.29	1200	1.23
10.0	2.53	17.59	6.37	1200	1.24
11.4	2.55	18.05	6.55	1200	1.26

*Trace of NO added.

TABLE III

EXPERIMENTAL DATA FOR THE METHANE-OXYGEN-HELIUM SYSTEM AT 2000°K, ONE ATMOSPHERE PRESSURE

O_2/CH_4	(H/D) Cone Height / Port Diameter	Q Volumetric Flow, 25°C 29.92" Hg (ft^3/hr)	u, Velocity at 25°C 29.92" Hg (ft/sec)	N_{Re} Reynolds Number	Burning Velocity (ft/sec)
0.783	4.09	20.31	7.36	1200	0.890
0.783	4.07	20.31	7.36	1200	0.890
1.2	7.40	3.77	1.37	80	0.764
1.2	1.73	5.83	2.11	125	0.610
1.2	2.76	7.88	2.86	165	0.509
1.2	4.27	12.00	4.35	255	0.506
1.6	1.61	7.07	2.56	120	0.761
3.0	0.633	5.07	1.84	95	1.14
4.0	1.96	8.76	3.17	195	1.07
5.0	0.281	8.00	2.90	210	2.53
6.0	0.353	8.00	2.90	240	2.37
7.0	0.402	8.00	2.90	280	2.[illegible]3
8.0	0.569	8.00	2.90	325	1.91
9.0	0.849	10.00	3.62	470	1.84
10.0	1.33	12.00	4.35	650	1.55
11.4	2.64	18.07	6.54	1200	1.22

TABLE IV

EXPERIMENTAL DATA FOR THE METHANE-OXYGEN-NITROGEN SYSTEM AT 2000°K, ONE ATMOSPHERE PRESSURE

O_2/CH_4	(H/D) Cone Height / Port Diameter	Q Volumetric Flow, 25°C 29.92" Hg (ft^3/hr)	u, Velocity at 25°C 29.92" Hg (ft/sec)	N_{Re} Reynolds Number	Burning Velocity (ft/sec)
4.0	2.58	18.20	6.59	1200	1.10
5.0	2.70	18.17	6.58	1200	1.21
6.0	2.66	18.14	6.57	1200	1.21

TABLE V

BURNER INLET GAS COMPOSITIONS FOR THE METHANE-OXYGEN-ARGON AND METHANE-OXYGEN-HELIUM SYSTEMS AT ADIABATIC FLAME TEMPERATURES OF 2000°K AND ONE ATMOSPHERE PRESSURE

Datum Temperature: 300°K

Mole Ratio Oxygen to Methane	Mole Ratio Inert to Methane	Mole Percent Methane	Mole Percent Oxygen	Mole Percent Inert
0.783	0	56.07	43.93	0
1.2	5.34	13.26	15.92	70.82
1.6	10.58	7.59	12.14	80.26
2.0	15.53	5.40	10.79	83.81
3.0	14.15	5.51	16.52	77.97
4.0	12.42	5.74	22.96	71.30
5.0	10.76	5.97	29.84	64.19
6.0	9.07	6.22	37.34	56.44
7.0	7.39	6.50	45.48	48.02
8.0	5.71	6.80	54.38	38.83
9.0	4.06	7.12	64.03	28.85
10.0	2.36	7.49	74.86	17.65
11.41	0	8.06	91.94	0

TABLE VI

EQUILIBRIUM COMPOSITIONS OF THE PRODUCTS FOR THE METHANE-OXYGEN-ARGON AND METHANE-OXYGEN-HELIUM SYSTEMS AT A THEORETICAL ADIABATIC FLAME TEMPERATURE OF 2000°K AND ONE ATMOSPHERE PRESSURE

Datum Temperature: 300°K

Products	Oxygen to Methane Ratio				
	0.783	1.2	1.6	2.0	3.0
CO_2	0.021811	0.027381	0.038448	0.051909	0.054734
CO	0.311311	0.092487	0.035205	0.001966	0.000320
H_2O	0.167000	0.140341	0.123474	0.106584	0.109296
A or He	0.000000	0.640046	0.778857	0.836814	0.779168
O_2	0.000000	0.000000	0.000002	0.001307	0.054866
H_2	0.498656	0.099172	0.023653	0.000844	0.000134
O	0.000000	0.000000	0.000001	0.000026	0.000172
H	0.001146	0.000511	0.000249	0.000047	0.000019
OH	0.000032	0.000061	0.000110	0.000501	0.001292

Products	Oxygen to Methane Ratio				
	4.0	5.0	6.0	7.0	8.0
CO_2	0.057115	0.059446	0.062010	0.064747	0.067773
CO	0.000231	0.000193	0.000170	0.000158	0.000145
H_2O	0.113796	0.118277	0.123282	0.128634	0.134532
A or H_3	0.712558	0.641399	0.563891	0.479845	0.387924
O_2	0.114355	0.178476	0.248195	0.323938	0.406735
H_2	0.000096	0.000080	0.000071	0.000065	0.000060
O	0.000248	0.000310	0.000366	0.000418	0.000468
H	0.000016	0.000014	0.000014	0.000013	0.000013
OH	0.001584	0.001805	0.002001	0.002184	0.002365

Products	Oxygen to Methane Ratio		
	9.0	10.0	11.41
CO_2	0.070931	0.074649	0.080325
CO	0.000138	0.000132	0.000126
H_2O	0.140808	0.148137	0.159350
A or He	0.288209	0.176300	0.000000
O_2	0.496785	0.597416	0.756500
H_2	0.000057	0.000055	0.000052
O	0.000517	0.000567	0.000638
H	0.000012	0.000012	0.000011
OH	0.002544	0.002732	0.003005

TABLE VII

BURNER INLET GAS COMPOSITIONS FOR THE METHANE-OXYGEN-NITROGEN SYSTEM AT AN ADIABATIC FLAME TEMPERATURE OF 2000°K AND ONE ATMOSPHERE PRESSURE

Datum Temperature: 300°K

Mole Ratio Oxygen to Methane	Mole Ratio Nitrogen to Methane	Mole Percent Methane	Mole Percent Oxygen	Mole Percent Nitrogen
4.0	7.71	7.87	31.48	60.65
6.0	5.56	7.96	47.75	44.29

TABLE VIII

EQUILIBRIUM COMPOSITION OF THE PRODUCTS OF COMBUSTION FOR THE METHANE-OXYGEN-NITROGEN SYSTEM AT A THEORETICAL ADIABATIC FLAME TEMPERATURE OF 2000°K AND ONE ATMOSPHERE PRESSURE

Datum Temperature: 300°K

Products	Oxygen to Methane Ratio 4.00	6.00
CO_2	0.078273	0.079292
CO	0.000273	0.000194
H_2O	0.156050	0.157700
N_2	0.602512	0.438633
O_2	0.153795	0.313637
H_2	0.000114	0.000081
O	0.000288	0.000411
H	0.000017	0.000015
OH	0.001997	0.002399
NO	0.006039	0.007358

TABLE IX

COMPARISON OF CALCULATED AND ESTIMATED ARGON-METHANE RATIOS FOR THE METHANE-OXYGEN-ARGON SYSTEM, 2000°K, ONE ATMOSPHERE PRESSURE

Oxygen to Methane	Calculated Argon to Methane	Estimated Argon to Methane	Percent Deviation
0.7835	0.000	--	--
1.2	5.339	5.320	-0.356
1.6	10.575	10.427	-1.399
2.0	15.534	--	--
3.0	14.154	13.884	-1.908
4.0	12.425	12.234	-1.537
5.0	10.755	10.584	-1.590
6.0	9.068	8.934	-1.478
7.0	7.393	7.284	-1.474
8.0	5.713	5.634	-1.383
9.0	4.055	3.984	-1.751
10.0	2.357	2.334	-0.975
11.414	0.000	--	--
		Average	-1.385

TABLE X

COMPARISON OF CALCULATED AND ESTIMATED NITROGEN-METHANE RATIOS FOR THE METHANE-OXYGEN NITROGEN SYSTEM, 2000°K, ONE ATMOSPHERE PRESSURE

Oxygen to Methane	Calculated Nitrogen to Methane	Estimated Nitrogen to Methane	Percent Deviation
0.7835	0.00	--	--
1.2	3.361	3.354	-0.208
1.6	6.670	6.575	-0.142
2.0	9.794	--	--
3.0	8.802	8.753	-0.557
4.0	7.706	7.713	+0.091
5.0	6.629	6.673	+0.664
6.0	5.564	5.633	+1.240
7.0	4.507	4.592	+1.886
8.0	3.365	3.552	+5.557
9.0	2.443	2.512	+2.824
10.5	0.926	0.952	+2.808
11.41	0.000	--	--

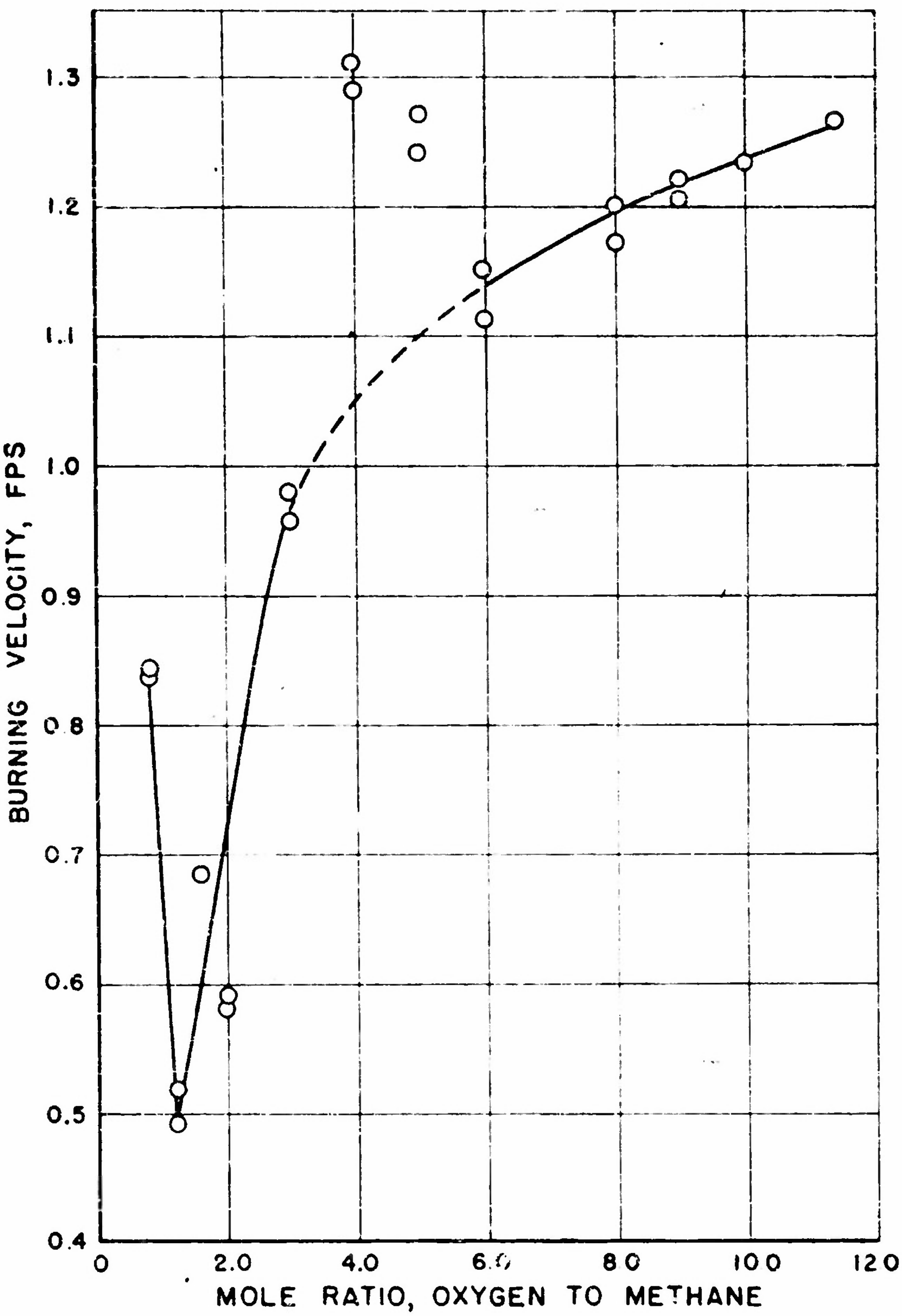

FIG. 1 BURNING VELOCITIES OF THE CH_4-O_2-A SYSTEM AT 2000°K, ONE ATMOSPHERE PRESSURE

PROJ. B-143
DATE 11-11-53

INSTITUTE OF GAS TECHNOLOGY

SCALE
A- 2733

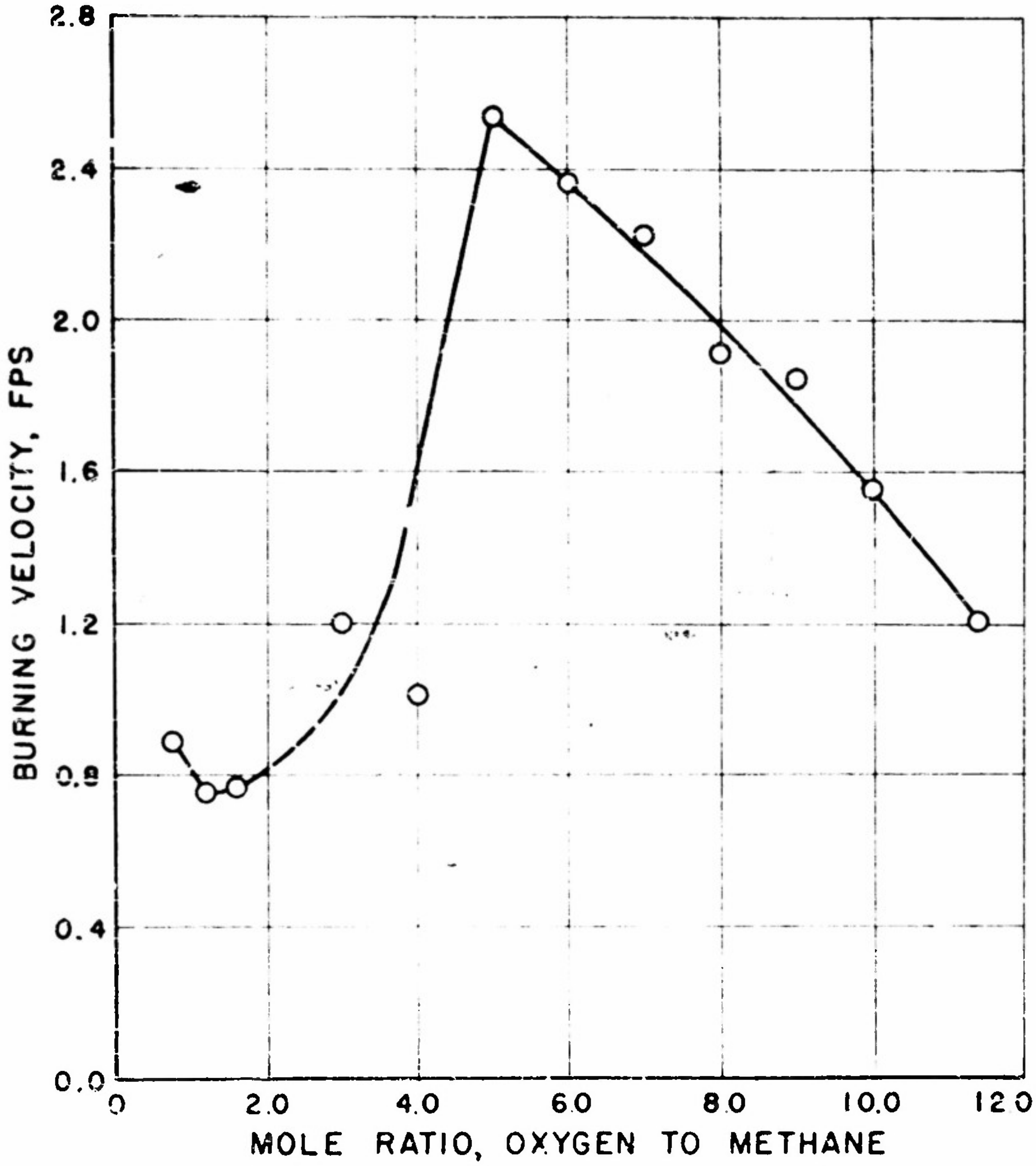

FIG. 2 - BURNING VELOCITIES OF THE CH_4-O_2-He SYSTEM AT 2000°K, ONE ATMOSPHERE PRESSURE

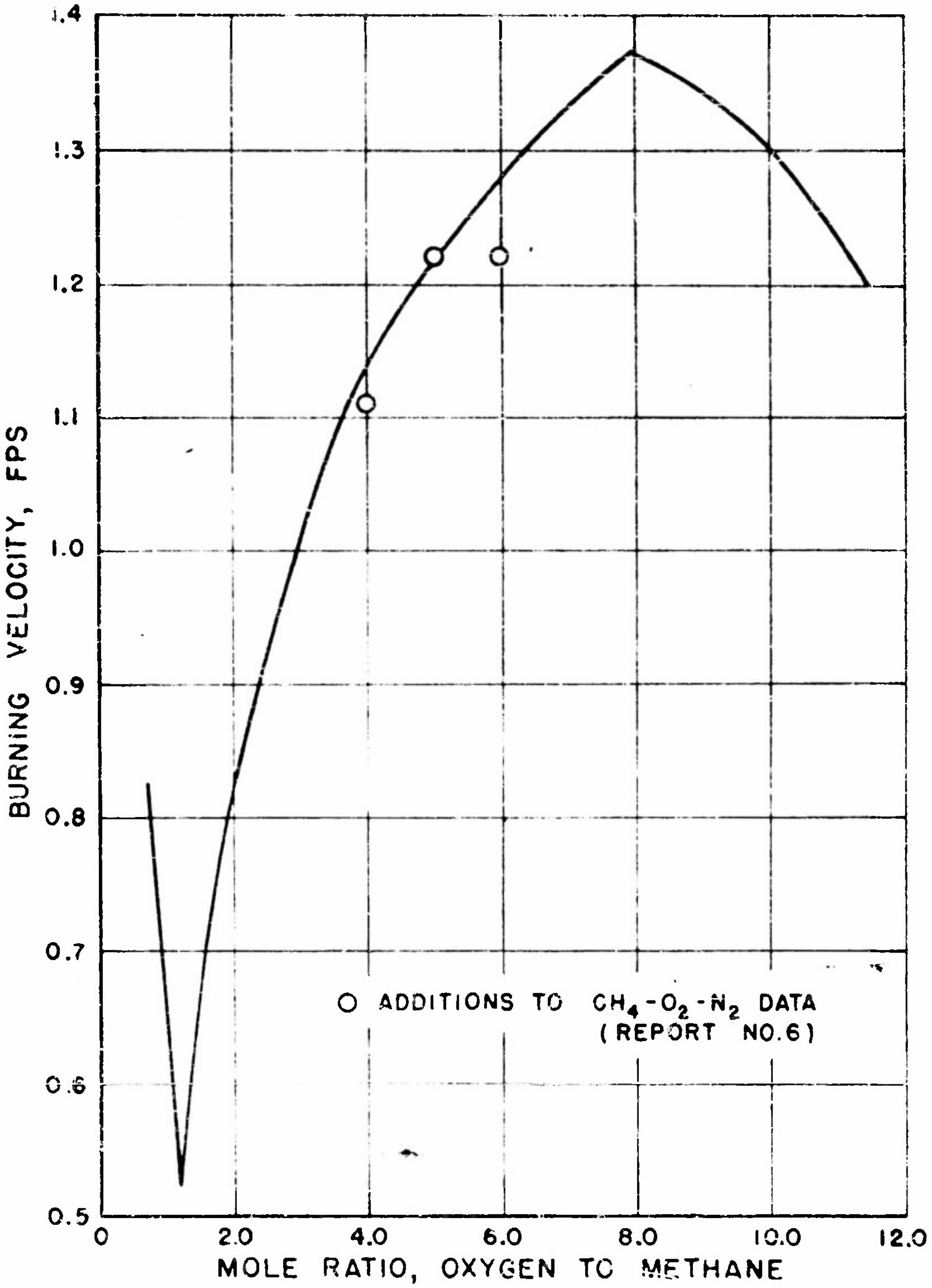

FIG 3 BURNING VELOCITIES OF THE CH_4-O_2-N_2 SYSTEM AT 2000°K, ONE ATMOSPHERE PRESSURE

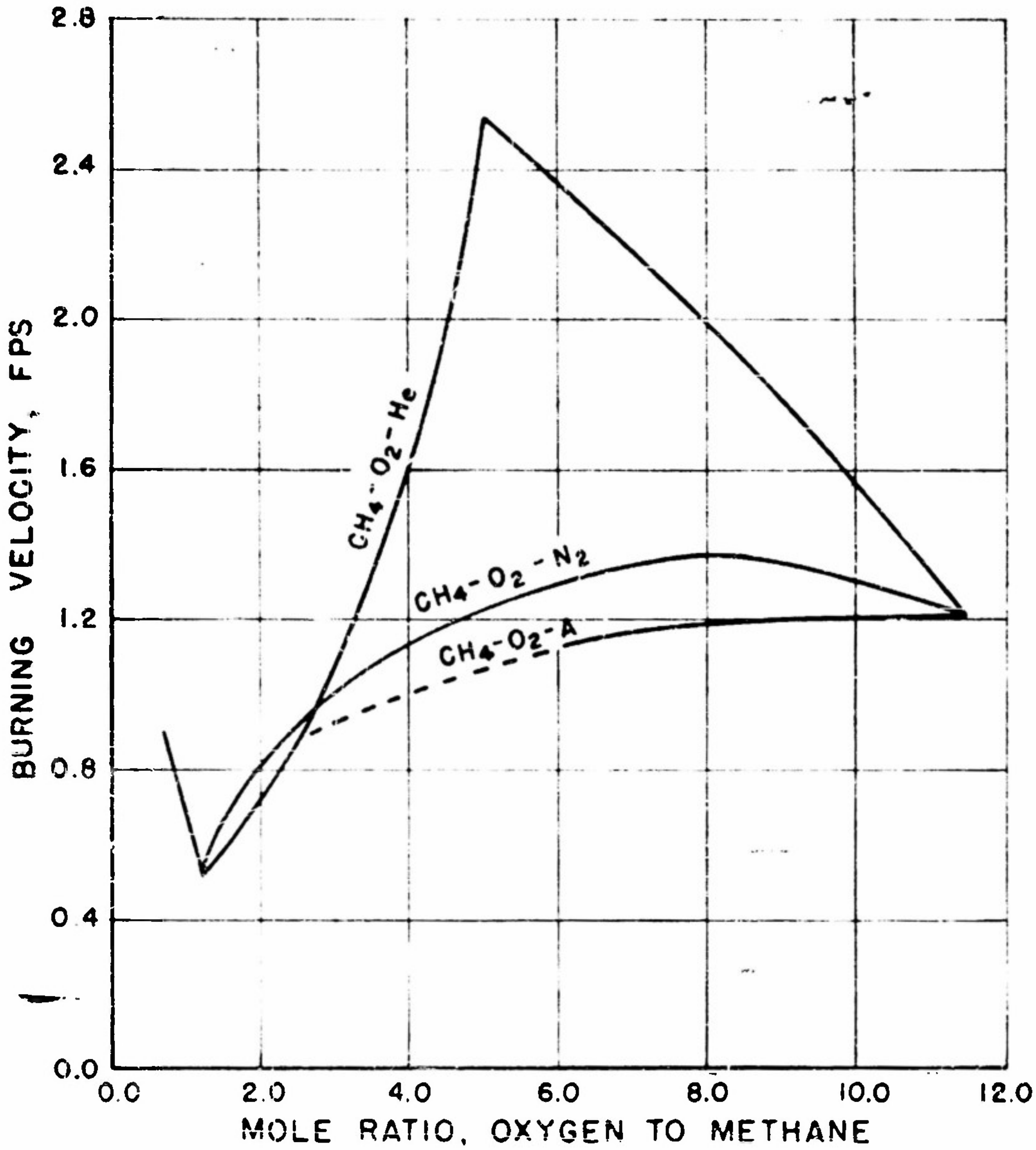

FIG. 4 COMPARISON OF METHANE-OXYGEN-INERT GAS SYSTEMS AT 2000°K, ONE ATMOSPHERE PRESSURE

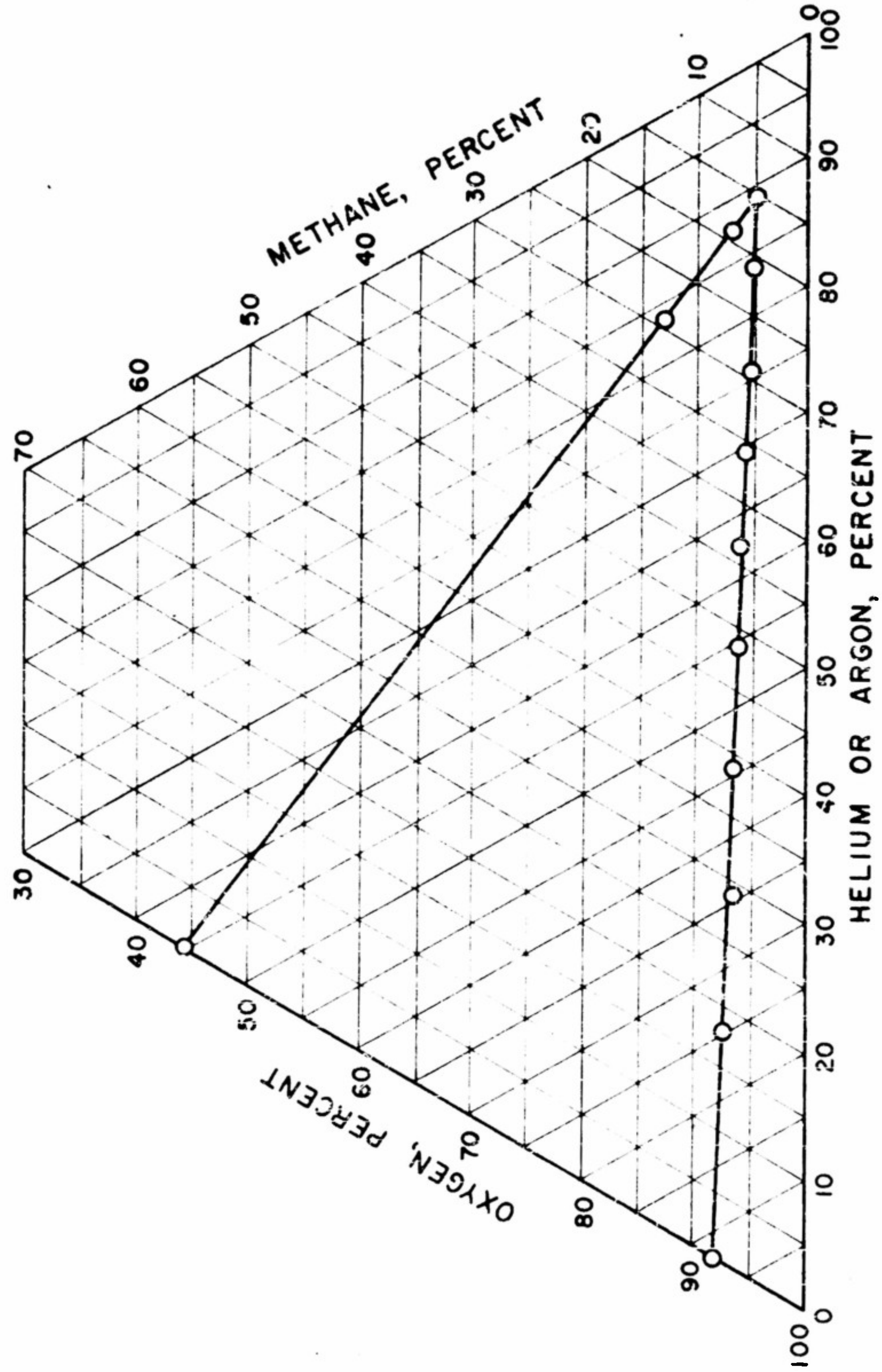

FIG. 5 - BURNER INLET GAS COMPOSITIONS FOR THE CH_4-O_2-A AND THE CH_4-O_2-He SYSTEMS AT 2000°K, ONE ATMOSPHERE PRESSURE

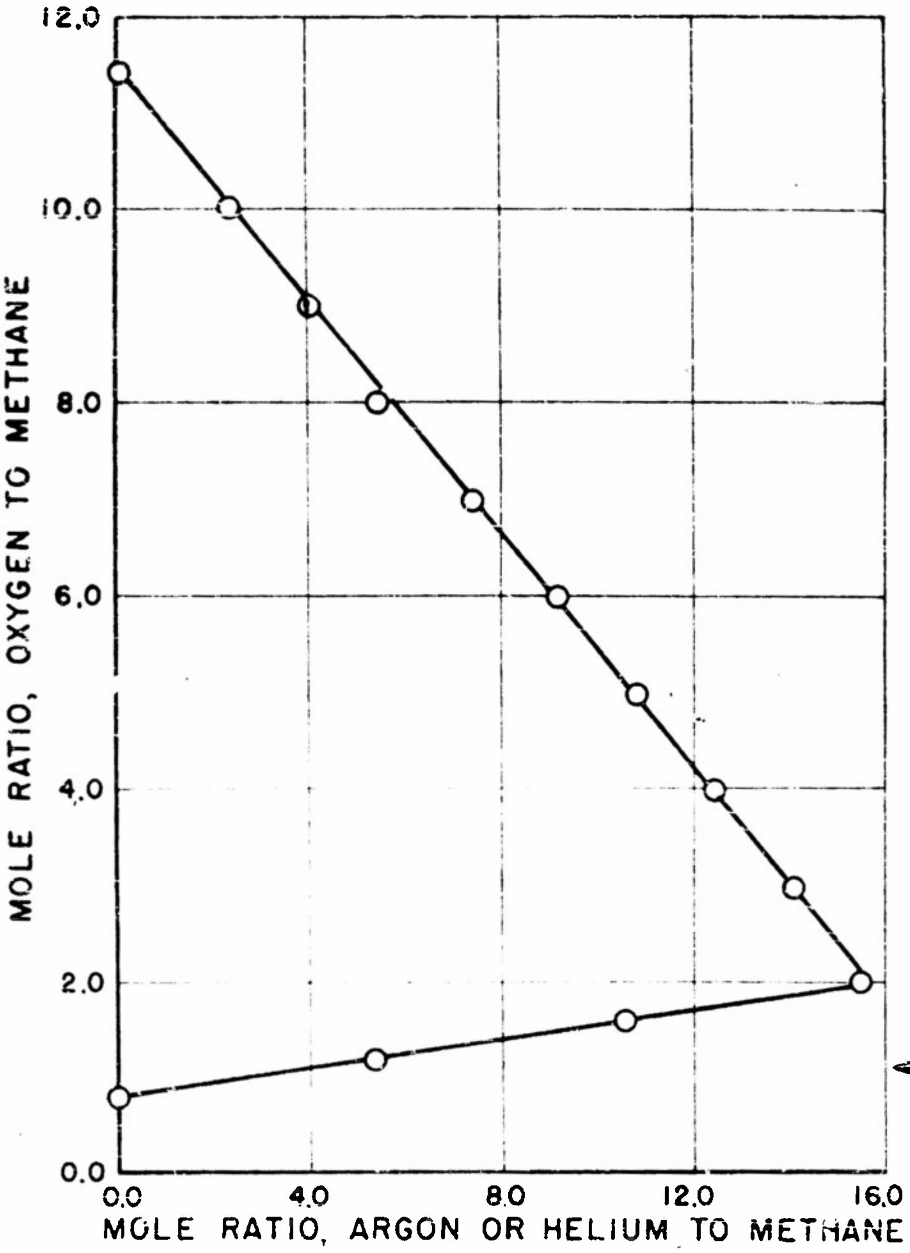

FIG. 6 - RATIOS OF THE COMPONENTS OF THE BURNER INLET GAS MIXTURES FOR THE CH_4-O_2-A AND CH_4-O_2-He SYSTEMS AT 2000°K, ONE ATMOSPHERE PRESSURE

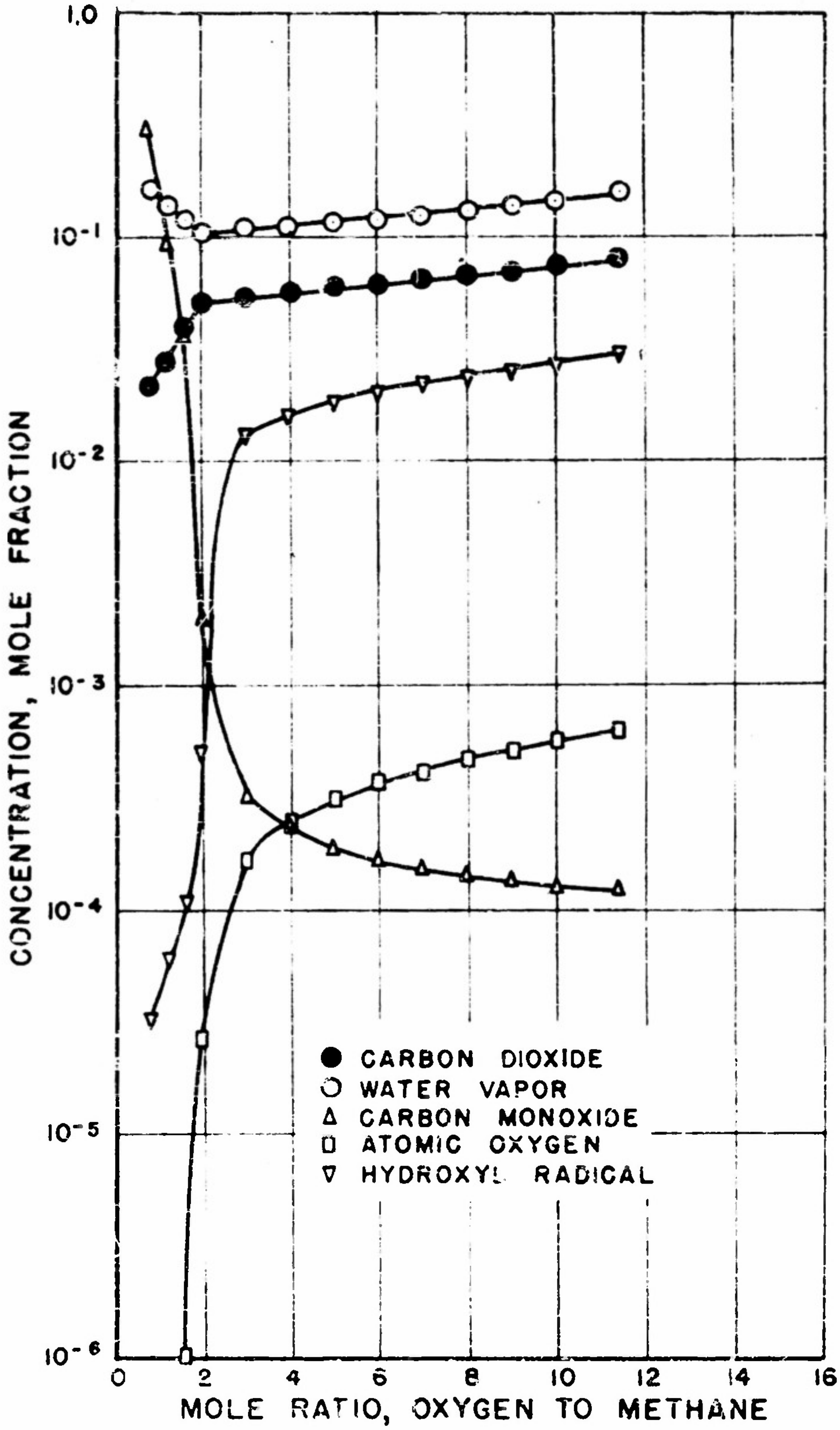

FIG. 7a EQUILIBRIUM COMPOSITION OF THE COMBUSTION PRODUCTS FOR THE CH_4-O_2-A & CH_4-O_2-He SYSTEMS AT 2000°K, ONE ATMOSPHERE

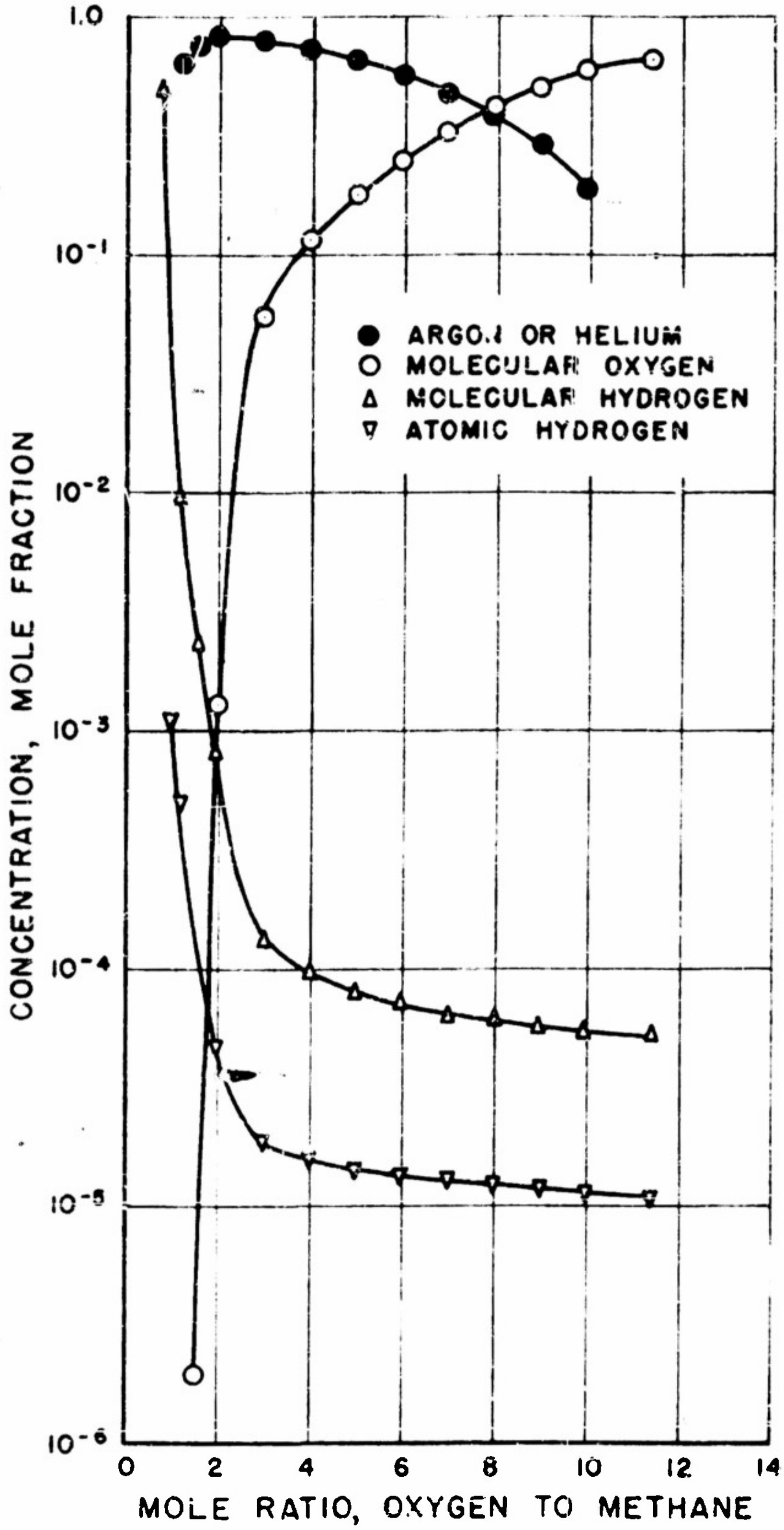

FIG. 7b EQUILIBRIUM COMPOSITION OF THE PRODUCTS FOR THE CH_4-O_2-A & CH_4-O_2-He SYSTEMS AT 2000°K, ONE ATMOSPHERE